



Severe tropical cyclones over southwest Pacific Islands: economic impacts and implications for disaster risk management

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Abstract

Tropical cyclones (TCs) are amongst the costliest natural hazards for southwest Pacific (SWP) Island nations. Extreme winds coupled with heavy rainfall and related coastal hazards, such as large waves and high seas, can have devastating consequences for life and property. Effects of anthropogenic climate change are likely to make TCs even more destructive in the SWP (as that observed particularly over Fiji) and elsewhere around the globe, yet TCs may occur less often. However, the underpinning science of quantifying future TC projections amid multiple uncertainties can be complex. The challenge for scientists is how to turn such technical knowledge framed around uncertainties into tangible products to inform decision-making in the disaster risk management (DRM) and disaster risk reduction (DRR) sector. Drawing on experiences from past TC events as analogies to what may happen in a warming climate can be useful. The role of science-based climate services tailored to the needs of the DRM and DRR sector is critical in this context. In the first part of this paper, we examine cases of historically severe TCs in the SWP and quantify their socio-economic impacts. The second part of this paper discusses a decision-support framework developed in collaboration with a number of agencies in the SWP, featuring science-based climate services that inform different stages of planning in national-level risk management strategies.

Keywords Tropical cyclones · Economic loss · Disaster risk management · Pacific Island Countries

1 Introduction

The southwest Pacific (SWP) Island nations (Fig. 1) are prone to catastrophic impacts of strong winds and storm surges, as well as extreme rainfall and associated flooding, during the passage of tropical cyclones (TCs). For example, severe TC *Winston* (February 2016) caused several fatalities and substantial damage to the infrastructure and agricultural

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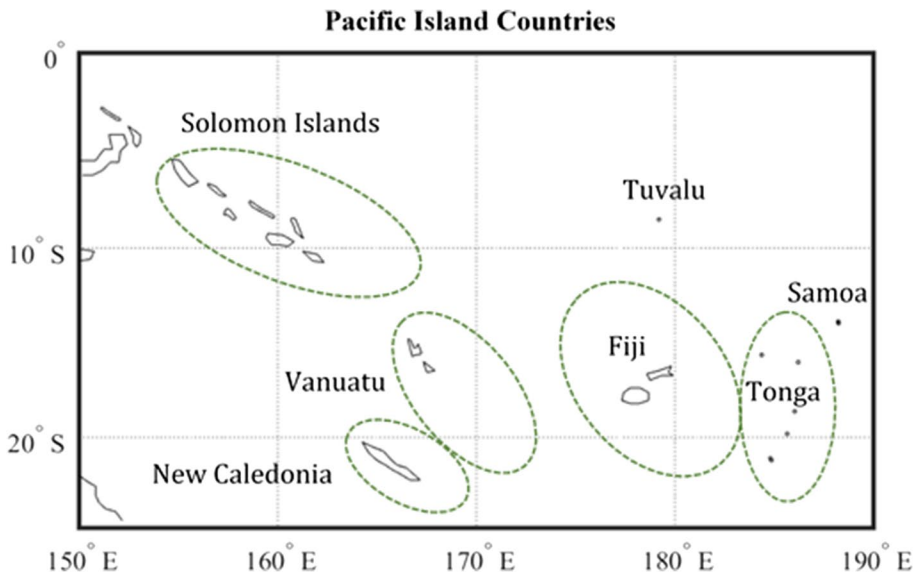


Fig. 1 Map of SWP Island nations

sectors across the Fiji Islands. The direct economic loss (or damage)¹ (hereafter referred to as ‘economic loss’ or simply ‘loss’) resulting from this cyclone accounted for ~20% of the country’s gross domestic product (GDP) (Esler et al. 2016). A year earlier, the economic loss from severe TC *Pam* (March 2015) exceeded 60% of Vanuatu’s GDP, derailing the country’s budget and fiscal position, and posing serious consequences for growth and development (McGee et al. 2015; World Bank 2018).

The impacts of TCs on societies in SWP Island nations are likely to be further exacerbated in a warming climate due to the increasing influences of greenhouse anthropogenic climate change, and through growing coastal population and infrastructure development (Lal 2011). For example, a number of studies have indicated that TCs are likely to become more intense with warming, and their rain-carrying capacity is also likely to increase substantially (see, for example, a review by Knutson et al. (2020)). Such changes, combined with accelerated sea-level rise, can cause increased rates of coastal flooding and storm surges, with potentially drastic economic impacts on societies and the country as a whole (Fig. 2, Woodruff et al. (2013)). Several studies have investigated the trends in the normalised economic loss (i.e. taking into account inflation, increasing population and wealth) due to TCs over the past decades in different regions around the globe. For example, in a recent study over the USA, Grinsted et al. (2019) revealed an emergent increasing trend in economic loss attributed to a detectable change in extreme storms due to global warming. In India, Raghavan and Rajesh (2003) also showed an increasing trend in the normalised economic loss due to TCs over Andhra Pradesh, but the trend there was attributable mainly to economic and demographic factors rather than

¹ Direct losses refer to the physical or structural impact caused by the disaster such as the destruction of infrastructure caused by the force of high winds, flooding, or ground shaking (United Nations 2016).

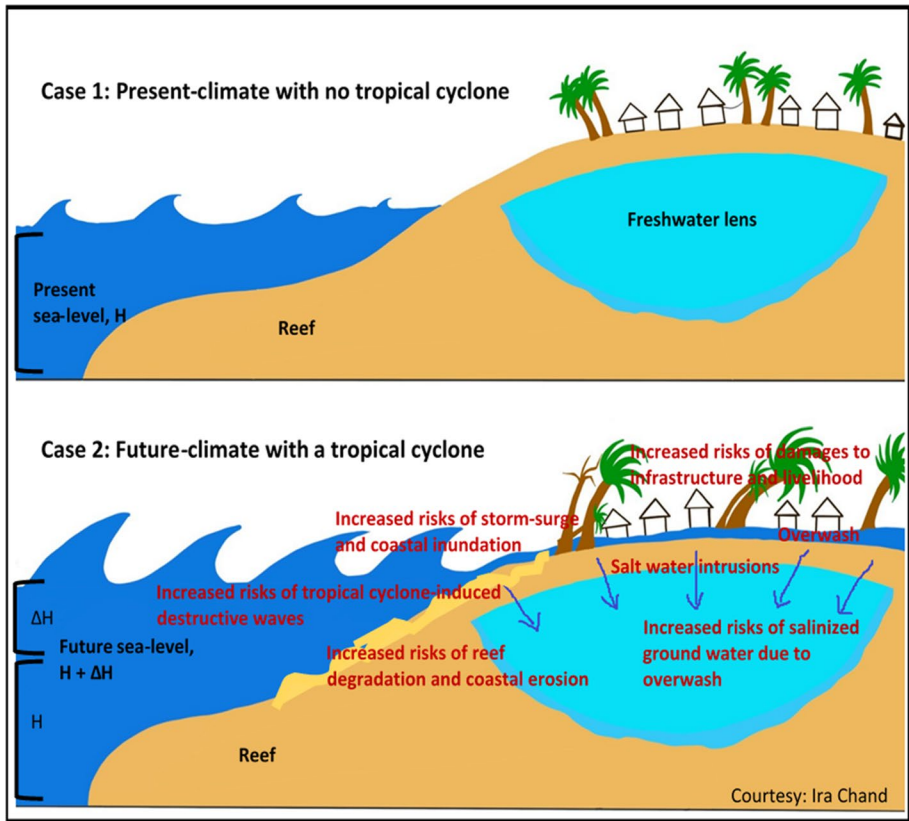


Fig. 2 Conceptual diagram of likely changes in TC-induced risks in a warming climate for two cases (based on Woodruff et al. 2013): case 1 represents a condition in present-climate without any TC, and case 2 represents a likely condition in future-climate in presence of a severe TC event

any long-term changes in TC characteristics. Similarly, over the mainland of China, Zhang et al. (2009) examined (without normalisation) the direct economic losses and casualties caused by landfalling TCs during the 1983–2006 period. They reported that even though the mortality from TCs shows no trend, the economic costs have increased rapidly during the nation's productivity boom.

In the SWP region, Mohan and Strobl (2017) used satellite measures of nightlight intensity to show the short-term impact of TC *Pam* on the economic activity of the affected islands across Vanuatu. However, as far as we are aware, no literature as yet exists that addresses the long-term changes in TC-related economic losses over the past decades for the SWP region. The overall objective of this work is twofold. We first examine the link between severe TCs and the consequent economic and human losses over several SWP island nations. In order to better capture year-to-year variability of the impacts (both economic losses and fatalities) associated with severe TCs, normalisation of the losses is performed to take into consideration inflation and changes in population and wealth (e.g. Pielke and Landsea (1998)). The other objective is to understand the role of local agencies (such as the National Disaster Management Office, NDMO and the National Hydrological and Meteorological Services, NHMS) in mitigating the losses

through provisions of early-warning systems and planning strategies at various stages of a TC event.

The rest of the paper is as follows. Section 2 presents the data and methodology, and Sect. 3 provides results and discussion. Section 4 summarises the findings of this research.

2 Data and methodology

Estimates of TC economic loss were obtained from the respective Government's TC Disaster Assessment and NHMS reports for the study period 1970–2018. Several of these reports are archived at the United Nations Office for the Coordination of Humanitarian Affairs' (UN-OCHA) 'ReliefWeb' portal.² Comprehensive TC impact loss data, such as those over the USA (e.g. Pielke et al. (2008)), are also archived at the Pacific Damage and Loss (PDaLo) portal,³ but due to some discrepancies with the available Government and NHMS reports (e.g. for TC *Gita* and TC *Winston* in 2018), such data are only used here for subjective verification purposes.

To best represent year-to-year variability, economic losses due to TCs are normalised to take into consideration inflation and changes in wealth and population over time. We use here the conventional approach (e.g. Pielke et al. (2008) and Grinsted et al. (2019)) to normalise TC impact data relative to the 2016 values (note here that 2016 is chosen subjectively as the reference year due to the impact of severe TC *Winston* in that year over the SWP region). The normalisation methodology assumes that losses are proportional to three factors: inflation, wealth and population. The general formula to normalise the loss in a particular year relative to the year of interest (in our case 2016) is as follows:

$$NL_{16} = L_y \times I_y \times W_y \times P_y \quad (1)$$

- NL_{16} is the normalised loss relative to the 2016 values.
- y is the year of TC impact.
- L_y is the loss in year y , in current-year dollars (and not adjusted for inflation).
- I_y is the inflation adjustment factor. This factor is computed using the Implicit Price Deflator for Gross Domestic Product (IPDGDP) and is the ratio of the 2016 IPDGDP to that in the TC impact year (e.g. Pielke et al. (2008)).
- W_y is the wealth factor, computed using the nominal GDP, the inflation adjustment factor, I_y , and the population.
- P_y is the population factor.

A detailed description of the normalisation procedure could be found in Pielke et al. (2008) and Grinsted et al. (2019). For the purpose of this study, IPDGDP, GDP and population data were obtained from the World Bank Open Data Online Portal.⁴ Moreover, TC intensity and track data were obtained from the Southwest Pacific Enhanced Archive for Tropical Cyclones (SPEARTC: Diamond et al. (2012)) database.

² <https://reliefweb.int/>

³ www.pdalo.net

⁴ <https://data.worldbank.org/>

Table 1 Australian and Fiji Region Intensity Scale of Tropical Storms (FMS 2009)

System type	10-min sustained wind speeds in km h^{-1}	Central Pressure (hPa)
Category 1 (CAT 1)	63–88	986–995
Category 2 (CAT 2)	89–117	971–985
Category 3 (CAT 3)	118–159	956–970
Category 4 (CAT 4)	160–199	930–955
Category 5 (CAT 5)	> 200	≤ 929

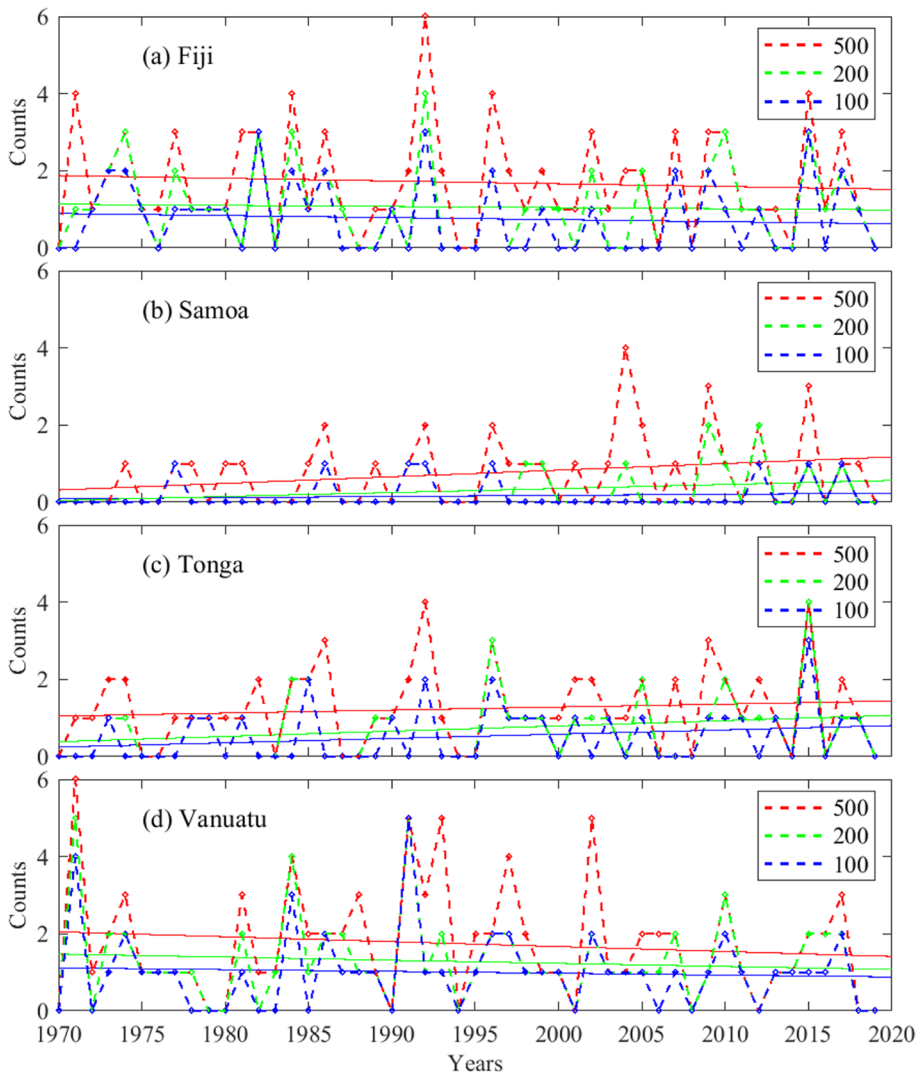
**Fig. 3** Time series of number of major (category 3 and above) TCs passing within 100, 200 and 500 km from Fiji (a), Samoa (b), Tonga (c) and Vanuatu (d)

Table 2 List of severe TCs (i.e. category 3 and above) passing within 50 km from the FSTV region for the period 1970–2018

Year	Mon	Day	TC Name	Min. press	Avg. wind speed	Country	Intensity
1972	10	24	BEBE	945	157	Fiji	Cat4
1979	3	22	MELI	945	180	Fiji	Cat4
1983	3	2	OSCAR	920	184	Fiji	Cat5
1983	3	24	SARAH	940	157	Fiji	Cat4
1985	1	17	ERIC	955	162	Fiji	Cat4
1986	12	29	RAJA	955	154	Fiji	Cat4
1990	11	27	SINA	960	171	Fiji	Cat3
1992	12	11	JONI	940	173	Fiji	Cat4
1993	1	2	KINA	955	167	Fiji	Cat4
1997	3	7	GAVIN	925	189	Fiji	Cat5
2008	1	28	GENE	946	159	Fiji	Cat4
2010	3	15	TOMAS	925	185	Fiji	Cat5
2012	12	17	EVAN	943	185	Fiji	Cat4
2016	2	20	WINSTON	884	278	Fiji	Cat5
1982	3	2	ISAAC	930	176	Tonga	Cat4
1998	12	26	CORA	960	145	Tonga	Cat3
2014	1	11	IAN	935	204	Tonga	Cat4
2016	1	1	ULA	944	185	Tonga	Cat4
2018	2	12	GITA	927	204	Tonga	Cat5
1990	2	4	OFA	925	186	Samoa	Cat5
1991	12	9	VAL	940	185	Samoa	Cat4
1997	1	11	EVAN	965	124	Samoa	Cat3
2018	2	9	GITA	927	204	Samoa	Cat5
1987	2	7	UMA	940	167	Vanuatu	Cat4
1992	1	9	BETSY	940	157	Vanuatu	Cat4
1993	3	30	PREMA	940	181	Vanuatu	Cat4
1996	3	24	BETI	935	168	Vanuatu	Cat4
1999	1	19	DANI	925	183	Vanuatu	Cat5
2004	2	26	IVY	936	168	Vanuatu	Cat4
2015	3	13	PAM	896	250	Vanuatu	Cat5

3 Results and discussion

3.1 Severe TCs in SWP island nations

This study focuses on TC-associated losses over three Pacific Island Countries, namely Fiji, Samoa, Tonga and Vanuatu (FSTV) mainly because economic loss data are readily available for these nations. The time series of the number of severe TCs (i.e. category 3 and above based on the Australian and Fiji TC intensity scale, Table 1), passing within 100, 200 and 500 km from the FSTV region for the period 1970–2018 are shown in Fig. 3. Over Fiji and Vanuatu, the number of severe TCs passing in close proximity shows a slight decreasing trend whereas for Samoa and Tonga there is a slight

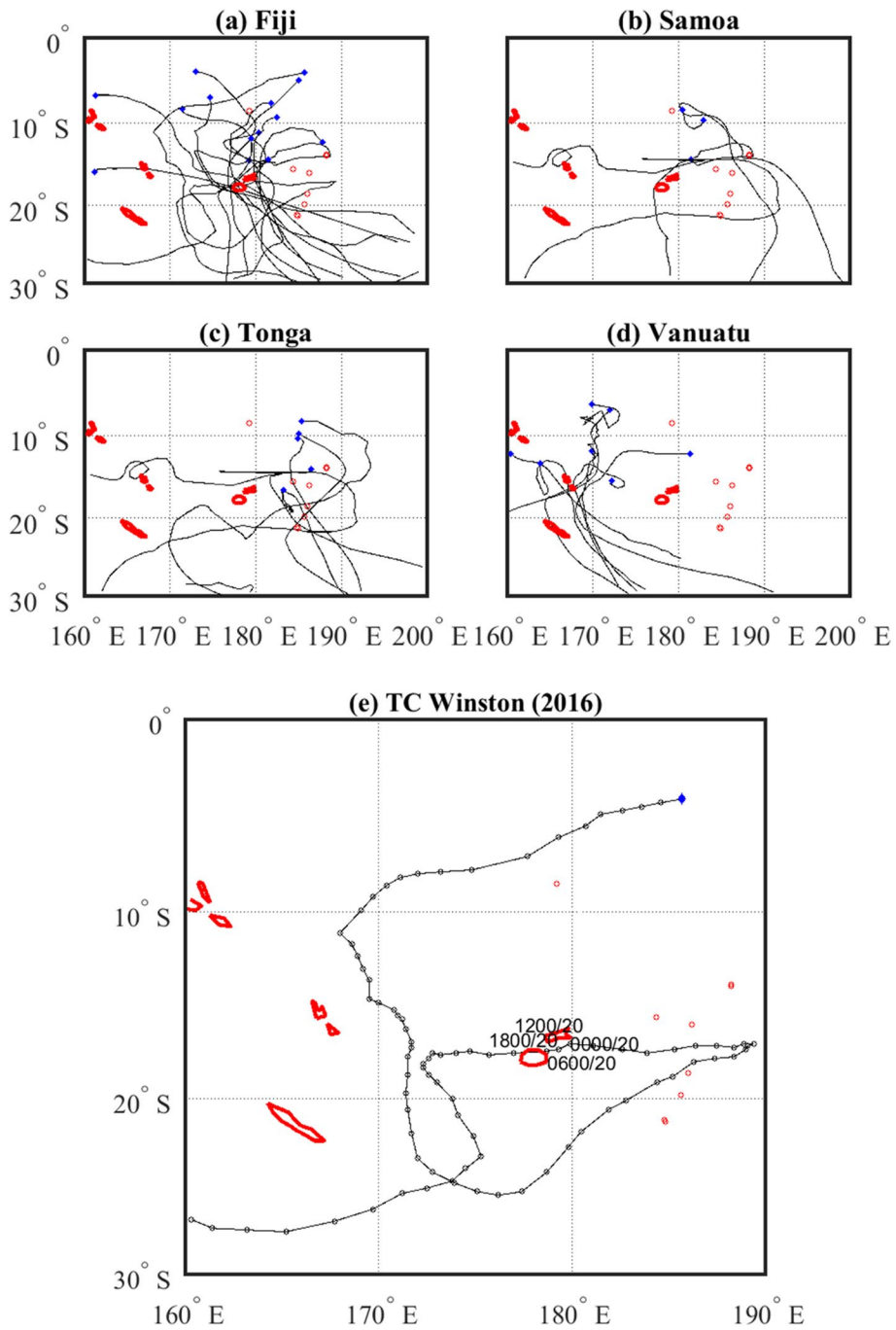


Fig. 4 (a–d) Tracks of severe TCs over the FSTV region (a–d) listed in Table 2 and (e) track of TC *Winston* (2016) also shown separately. The blue diamond markers show genesis positions

Table 3 TC-associated economic loss over the FSTV region—in millions of local currency (LC) and USD. L_y is the loss for the year ‘y’ whereas NL is the loss, L_y , normalised with respect to 2016 values

YYYY	MM	DD	TC name	Country	L_y (LC)	L_y (USD)	NL (LC)	NL (USD)
1972	10	24	BEBE	Fiji	22.5	18.6	350.3	289.0
1979	3	22	MELI	Fiji	—			
1983	3	2	OSCAR	Fiji	148	139.0	649.7	610.1
1985	1	17	ERIC	Fiji	40	34.3	172.8	148.3
1986	12	29	RAJA	Fiji	16	14.0	61.1	53.5
1990	11	27	SINA	Fiji	26	18.5	95.9	68.2
1992	12	11	JONI	Fiji	2	1.6	6.4	5.1
1993	1	2	KINA	Fiji	170	110.0	512.5	331.6
1997	3	7	GAVIN	Fiji	33.4	23.7	78.6	55.8
2003	2	13	AMI	Fiji	104.4	51.2	222.2	109.0
2008	1	28	GENE	Fiji	51	35.0	71.4	49.0
2010	3	15	TOMAS	Fiji	84	43.6	131.9	68.4
2012	12	17	EVAN	Fiji	194.9	108.0	241.9	134.1
2016	2	20	WINSTON	Fiji	1990	900.0	1990.0	900.0
1982	3	2	ISAAC	Tonga	18	17.1	116.3	110.5
1998	12	26	CORA	Tonga	19.6	12.0	41.7	25.5
2001	12	31	WAKA	Tonga	104.2	51.3	230.6	113.5
2014	1	11	IAN	Tonga	90.2	48.0	81.5	43.4
2018	2	12	GITA	Tonga	356.1	164.1	317.2	146.2
1990	2	4	OFA	Samoa	355.5	150.0	2259.6	953.4
1991	12	9	VAL	Samoa	700	280.0	4455.2	1782.1
2012	12	12	EVAN	Samoa	465	203.9	488.7	214.3
2018	2	9	GITA	Samoa	26.1	10.0	25.4	9.7
1987	2	7	UMA	Vanuatu	15,579	150.0	95,775.5	922.2
1992	1	9	BETSY	Vanuatu	240.18	2.0	984.9	8.2
1993	3	30	PREMA	Vanuatu	612.75	5.0	2620.4	21.4
1996	3	24	BETI	Vanuatu	4.5	0.0	14.8	0.1
1999	1	19	DANI	Vanuatu	396.84	3.0	1191.0	9.0
2004	2	26	IVY	Vanuatu	427.6	3.8	942.3	8.4
2015	3	13	PAM	Vanuatu	63,200	600.0	66,913.9	635.3

increasing trend (note, these trends are not statistically significant at the 95% confidence level).

Table 2 shows the meteorological parameters of severe TCs passing within 50 km of the FSTV region, and the respective tracks of those TCs are shown in Fig. 4(a–d). Of all TCs during the period 1970–2018, *Winston* was the most severe TC in the region with a record minimum seal level pressure of 884 hPa and 10-min sustained windspeed of 278 km h⁻¹ which directly impacted Fiji on the 20th of February 2016. TC *Pam*, with a minimum sea level pressure of 896 hPa and 10-min sustained windspeed of 250 km h⁻¹, was the most severe storm that has impacted Vanuatu on the 13th of March 2015. TC *Ofa*, with a minimum pressure of 925 hPa, was the most severe TC to affect Samoa on the 4th of February 1990 whereas *Gita* (with a minimum pressure of 927 hPa and 10-min sustained windspeed of 204 km h⁻¹ at some point in its lifetime) was the most severe storm to affect Tonga on

the 12th of February 2018. All of these TCs had significant impact over the respective regions as will be shown in the following sections.

3.2 Economics losses over the FSTV region

Table 3 shows the estimated and normalised losses, adjusted to the 2016 values, associated with severe TCs (listed in Table 2) impacting the FSTV region. The estimated losses show large temporal differences, even after taking into consideration inflation, wealth and population factors. Losses (i.e. inflation corrected) due to the most recent TCs are very high over some of the nations. Over Fiji, losses due to TC *Winston* in 2016 amounted to FJD \$1.990 billion compared with severe TCs *Oscar* (1983) and *Kina* (1993) where the losses were FJD 0.649 billion and FJD 0.513 billion respectively; clearly, the loss associated with TC *Winston* was over three times greater than the other two severe events. The total loss due to TCs in the last decade (i.e. 2010–2019) is also significantly larger than that in the previous decades: FJD 2.363 billion (2010–2019); FJD 0.294 billion (2000–2009); FJD 0.6934 billion (1990–1999); 0.884 billion (1980–1989); and FJD 0.350 billion (1970–1979).

Similarly, based on the data analysed here, the highest loss for Tonga was due to TC *Gita* in 2018 (~TOP 0.317 billion) followed by TC *Waka* in 2001 (TOP 0.231 billion). Samoa did not experience any major TC-related losses in the last two decades. However, during the period 1990–1999, we saw two back-to-back severe TCs over the country: TC *Ofa* (1990) and TC *Val* (1991) that caused damages close to WST 2.3 billion and WST 4.5 billion respectively.

TC-associated loss over Vanuatu, similar to Samoa, does not show any trend over the past decades. While loss due to the recent TC *Pam* (2015) was the largest in the current-year vanu (VUT 63.20 billion), loss after normalisation was the largest (VUT 95.78 billion) for TC *Uma* (1987). Following TC *Uma* and *Pam*, the major normalised impact losses were 2.62 and 1.91 billion vanu associated with TC *Prema* (1993) and TC *Dani* (1999) respectively. These findings in general show that, except for Fiji, clear increasing trends in TC economic losses for other countries are absent. While we acknowledge that the lack of complete economic data for some countries may affect the trends, improved DRR efforts by various sectors may have played a critical role in suppressing economic loss and fatalities (see subsequent discussions).

3.3 Disaster response and fatalities

The number of severe TC-related fatalities can provide an indirect measure of a country's level of preparedness and response for a particular event. Table 4 shows the fatalities related to the severe TCs (that are listed in Table 2) impacting the FSTV region. For Fiji, the largest TC-related fatality was 52 during TC *Meli* (1979), followed by 44 fatalities that were during the passage of severe TC *Winston* (2016). TC *Eric* (1985) and TC *Kina* (1993) recorded total fatalities of 28 and 26 respectively, whereas those associated with other TC events were below 20 deaths. For Samoa, the number of recorded TC-related deaths was mainly below 10, except for the severe TC *Evan* (2012) that caused 14 deaths in the country. For Tonga, the largest number of fatalities (i.e. 6) was also during the passage of TC *Evan* (2012), whereas, for Vanuatu, the largest number of TC-related deaths was 50 during the passage of TC *Uma* (1987), followed by 15 fatalities during TC *Pam* (2015).

Losses in human lives translate to losses in GDP over time. However, economic loss values due to TCs, such as those provided in Table 3, do not take this into consideration

Table 4 Fatalities associated with severe TCs listed in Table 2

Year	Mon	Day	TC Name	Country	Deaths (D)	NL (LC)	NL (USD)	$D/NL (\times 10^{-2})$	$D \times NL$
1972	10	24	BEBE	Fiji	19	350.3	289.0	5.42	6656
1979	3	22	MELI	Fiji	52	—	—		
1983	3	2	OSCAR	Fiji	9	649.7	610.1	1.39	5847
1985	1	17	ERIC	Fiji	28	172.8	148.3	16.20	4838
1986	12	29	RAJA	Fiji	1	61.1	53.5	1.64	61
1990	11	27	SINA	Fiji	0	95.9	68.2	0.00	
1992	12	11	JONI	Fiji	1	6.4	5.1	15.53	6
1993	1	2	KINA	Fiji	26	512.5	331.6	5.07	13,324
1997	3	7	GAVIN	Fiji	18	78.6	55.8	22.89	1415
2003	2	13	AMI	Fiji	14	222.2	109.0	6.30	3111
2008	1	28	GENE	Fiji	8	71.4	49.0	11.21	570
2010	3	15	TOMAS	Fiji	3	131.9	68.4	2.27	395
2012	12	17	EVAN	Fiji	0	241.9	134.1	0.00	0
2016	2	20	WINSTON	Fiji	44	1990.0	900.0	2.21	87,560
1982	3	2	ISAAC	Tonga	6	116.3	110.5	5.16	697
1998	12	26	CORA	Tonga	0	41.7	25.5	0.00	
2001	12	31	WAKA	Tonga	1	230.6	113.5	0.43	230
2014	1	11	IAN	Tonga	1	81.5	43.4	1.23	81
2018	2	12	GITA	Tonga	2	317.2	146.2	0.63	634
1990	2	4	OFA	Samoa	7	2259.6	953.4	0.31	15,817
1991	12	9	VAL	Samoa	13	4455.2	1782.1	0.29	57,917
2012	12	12	EVAN	Samoa	14	488.7	214.3	2.86	6842
2018	2	9	GITA	Samoa	0	25.4	9.7	0.00	0
1987	2	7	UMA	Vanuatu	50	95,775.5	922.2	0.05	4,788,773
1992	1	9	BETSY	Vanuatu	1	984.9	8.2	0.10	984
1993	3	30	PREMA	Vanuatu	3	2620.4	21.4	0.11	7861
1996	3	24	BETI	Vanuatu	0	14.8	0.1	0.00	0
1999	1	19	DANI	Vanuatu	2	1191.0	9.0	0.17	2382
2004	2	26	IVY	Vanuatu	1	942.3	8.4	0.11	942
2015	3	13	PAM	Vanuatu	15	66,913.9	635.3	0.02	1,003,709

(Raghavan and Rajesh 2003). Moreover, trends in fatalities are an excellent indicator of the improvements in the overall DRM and DRR over time. Reasonable metrics (or indices) to measure this are as follows: (i) the ratio of fatality (D_y) to economic loss (NL_y) and (ii) the product of the two (i.e. $D_y \times NL_y$; Raghavan and Rajesh (2003)). A decreasing trend in the former means fewer deaths per unit of economic loss which would signify improvements in DRM and DRR. In the latter metric, a decreasing trend would signify either a decrease in D_y or NL_y or both.

Table 4 shows the fatality indices related to TCs that are listed in Table 2. Over Fiji, the D/NL index shows a decreasing trend that peaked during TC *Gavin* (1997), and this indicates an overall improvement of DRR over time. The $D \times NL$ factor peaks during TC *Winston* (2016), which could be associated with an exceptionally large impact loss. For Tonga and Vanuatu, both the indices show a decreasing trend, signifying improvements in DRR,

whereas for Samoa, the results are mixed: the D/NL index shows no trend but the $D \times NL$ shows a decreasing trend, though a larger sample size is needed to make any confident conclusion here.

3.4 Current responsibilities of NHMS

The role of the local NHMS is critical for DRM and DRR, particularly with those associated with TCs and extreme rainfall. The Fiji NHMS (known as the Fiji Meteorological Services or FMS) is also designated as the Regional Specialised Meteorological Centre (RSMC) by the World Meteorological Organization (WMO) under the World Weather Watch Program specialising in TCs. With this designation, the Fiji NHMS is responsible for the provision of ‘first-level’ information on TCs, such as basic information covering TC’s present and forecast positions, as well as movement and intensity in the SWP region, from 0° to –25°S, and 160°E to 120°W. Nonetheless, the general roles of the individual NHMSs in the region include provision of essential weather, including TC-related services, and climate and hydrological services which we briefly discuss here.

Foremost, the NHMSs are responsible for continuous monitoring of weather and providing daily forecasts to the general public, marine and aviation. The FMS in particular is responsible for providing these services to Fiji, the Cook Islands, Kiribati, Nauru, Niue, Tokelau, Tonga and Tuvalu.

During TCs, the NHMSs issue Special Weather Bulletins (SWB) every 6 h upon issuance of a TC alert, the frequency of which is usually increased to every 3 h with the upgrade to a TC warning. Together with that, TC threat and forecast maps are issued every 6 h. Alerts for heavy rainfall are also issued if the estimated 24-h rainfall exceeds 100 mm within the next 48 h (but not before 24 h) and these could later be upgraded to a warning if the estimated rainfall exceeds 100 mm within the next 24 h.

The NHMSs also have Climate Services Division whose operations include the (1) National Climate Data Centre, and (2) National Climate Monitoring and Prediction Centre. Within the framework of the climate services delivery, the NHMSs are responsible for monitoring of climate variability and change. They also promote the effective use of these data and provide consultative services for planning, research and decision-making processes that are critical for socio-economic development.

The Climate Monitoring and Prediction Centre issues regular climate monitoring products, including updates on El Niño–Southern Oscillation (ENSO) status and monthly-to-seasonal outlooks for atmospheric variables such as rainfall and air temperature. It also issues a regular ocean outlook which includes information on sea surface temperatures (SSTs), fisheries convergence zone, sea level, coral bleaching and astronomical tide predictions. Specialised monthly-to-seasonal products for sectors such as agriculture (e.g. sugar cane in Fiji), energy (e.g. hydroelectricity), health (e.g. Malaria Early Warning System) and climate data are provided when needed or upon request for decision-makings (e.g. engineering designs within infrastructure departments, planning in the agriculture sector, NDMO and health).

Hydrological Services have also been recently introduced in some of the NHMSs (e.g. Fiji) to issue flood advisories. These are mostly based on river-level monitoring through telemetered systems, and the FMS has, in particular, incorporated a flash flood guidance system with the assistance of the WMO.

Most of the above services and products are delivered routinely to all sectors, including communities, government, media organisations and other Meteorological Services in

the region and the world. Social media platforms and mobile phone applications, together with animations and videos, are increasingly used to disseminate these weather, climate and hydrological information. While these services are publicly available, the NDMO is one of the key specialised users of it. During any anticipated deterioration of weather, climate and hydrological condition, the NHMS provides regular briefings to NDMO, including face-to-face communication and product updates. It is also important to note here that all the regional NHMSs coordinate their scientific and technical programme and activities through the Pacific Meteorological Council (PMC⁵).

3.5 Preparedness and disaster response: TC Winston (2016) as a case study

To reduce the impacts from TCs, a series of actions is mandatory before, during and after the passage of TCs. Here we use Severe TC *Winston* (2016) as an example to illustrate the preparedness and response by the NHMS and NDMO during a TC event over the SWP region.

3.5.1 TC history and disaster preparedness

TC *Winston*, a category 5 system in the Australian TC intensity scale, made landfall on 20 February 2016 at 0600 UTC over Viti Levu, Fiji, directly affecting the region of Rakiraki (see the track in Fig. 4(e)). The central pressure and 10-min sustained windspeed during the landfall were 886 hPa and 280 km h⁻¹ respectively. Following is a brief history of TC *Winston* before making landfall over Fiji and the disaster preparatory actions undertaken by the relevant organisations such as the NDMO.

The FMS started monitoring tropical disturbance (TD) '09F' on 7 February 2016, which had developed near 8.4°S and 170.6°E (far northwest of Fiji: FMS (2016m)). Early on 11 February, the FMS upgraded the TD to a category 1 TC and named it 'Winston' (FMS 2016g). Later, around 1200 UTC on the same day, *Winston* intensified into a category 2 TC, as a small, well-defined eye developed within the deepening convection (FMS 2016h). On 12 February, *Winston* rapidly intensified into a category 3 TC by 0600 UTC and then a category 4 TC by 1200 UTC (FMS 2016i). By 0000 UTC on 15 February, TC *Winston* reduced in intensity and became a category 2 system (FMS 2016j) before upgrading to a category 3 system at 1800 UTC on the 16th (FMS 2016k). By 18 February, the intensifying system was translating towards Fiji (FMS 2016f). It reached category 5 level at 0600 UTC on the 19th, with 10-min sustained winds reaching 205 km h⁻¹ (FMS 2016l). Around 1800 UTC, *Winston* passed over the Fijian island of *Vanuabalavu* with a momentary wind gust of 306 km h⁻¹ (FMS 2016a). TC *Winston* attained its maximum (sustained) intensity around 0000 UTC on 20 February with 10-min sustained winds of 280 km h⁻¹ and a central pressure of 884 hPa (SPEARTC). It made landfall over *Rakiraki* around 0600 UTC at peak intensity (SPEARTC) making it the only known category 5 TC (until 2018), to directly impact Fiji, and therefore the most intense storm on record to strike the nation (SPEARTC). It also marked the strongest landfall by any TC in the South Pacific basin (SPEARTC), and one of the strongest landfalls worldwide since the modern era of global records began in 1970 (Liberto 2016).

⁵ <https://www.pacificmet.net/pmc>

The FMS started issuing TC warnings for the Fiji group on 14 February (FMS 2016c). However, these were called off on 16 February as *Winston* moved away from the nation (FMS 2016b). TC warnings commenced again on 18 February after *Winston* started moving towards Fiji for the second time and these warnings were issued for the northern and eastern islands (FMS 2016d). The northern islands in the TC's direct path were placed under severe hurricane warnings on 19 February (FMS 2016e). The NDMO activated, in total, more than 700 evacuation centres throughout the nation (RNZ 2016) and the Republic of Fiji Military Forces (RFMF) were placed on standby for relief efforts (Talei 2016). On the afternoon of 20 February, a state of emergency was declared (Swami 2016), a nationwide curfew was enacted starting at 1800 LT (Singh 2016) and public transportation services were suspended across Viti Levu.

3.5.2 Fatalities

A total of 44 fatalities resulted as a direct consequence of TC *Winston*. While there is no difference in fatality based on gender, differences do exist when age and ethnicity factors are considered (Esler et al. 2016). For the age group below 15 years, the fatality is ~13%, but it is 50% for the 15–64-year group. For the age group 65 and above, which makes just 4% of the total Fijian population, the mortality is disproportionately high at ~37% (Esler et al. 2016).

With respect to ethnicity, a larger percentage of fatalities was observed for the iTaukei (first nation) group in comparison with the Indian descendant (Indo-Fijian) group. For the iTaukei group, which comprises 57% of the Fijian population, this figure stands at 97% in comparison to 3% for the Indo-Fijian group that make 37% of the population (Esler et al. 2016). Even after stratifying into regions based on ethnicity, this is still valid. Areas such as the *Koro Island*, where 21% of deaths occurred, are largely inhabited by iTaukei. On the other hand, in areas which are primarily populated by Indo-Fijians, e.g. *Ba* (54%), the mortality amongst the iTaukei group was still higher (Esler et al. 2016). This discrepancy in the fatality between the ethnic groups requires further investigation and appropriate measures for future improved TC-related disaster responses.

3.5.3 Implications for NDMO and NMHS and their production and delivery of climate services to support decision-making in DRM: lessons learned and future directions

While necessary preparatory and disaster response actions, which included early warnings both to decision-makers and to the general public, were undertaken, the resultant 44 deaths (in particular, the high rate of mortality in the iTaukei group) show that there are still some shortcomings in the approach and appropriate actions need to be taken to correct these shortcomings. Some of the actions that could be stipulated to help improve DRR and disaster preparedness are outlined as follows:

- Increase public awareness and individual preparedness

Since TCs are a common phenomenon in the SWP region, science-based services such as the NHMS could work closely with the Ministry of Education to develop meteorology-related syllabuses for schools. Schools could also organise short visits to the NHMS throughout the academic year to give more insight into what is being taught about meteorology in their curriculum. Schools could also annually invite NHMSs to deliver pres-

Fig. 5 Schematic representation of the linkages between natural climate variability, human-induced global warming and tropical cyclones. Note that this diagram is not exclusive and does not quantify the changes, but instead demonstrates how different climatic factors may interact to affect TC characteristics and associated impacts over the SWP region (¹Vecchi et al. 2006; ²Yeh et al. 2009; ³Power and Kociuba 2011; ⁴Kim and Yu 2012; ⁵Sugi et al. 2012; ⁶Sugi and Yoshimura 2012; ⁷Tokinaga et al. 2012; ⁸Church et al. 2013; ⁹Hartmann et al. 2013; ¹⁰Tory et al. 2013; ¹¹Woodruff et al. 2013; ¹²Cai et al. 2014; ¹³Kossin et al. 2014; ¹⁴Lucas et al. 2014; ¹⁵Walsh et al. 2016; ¹⁶Chand et al. 2017; ¹⁷Taupo and Noy 2017; ¹⁸Chand 2018; ¹⁹Kossin 2018; ²⁰Sharmila and Walsh 2018; ²¹Andrew et al. 2019; ²²Chand et al. 2020)

entations on early warning alerts and potential actions expected from the general public, particularly if there is no meteorology-related curriculum. Moreover, science-based services (e.g. NHMS) and other relevant organisations (e.g. NDMO) could organise workshops discussing key concepts surrounding TCs, DRR, preparedness and response. A short book or pamphlet about TCs in various languages could also help increase public awareness particularly with regard to the impacts of TCs.

- Upgrade the current tools used to observe and forecast weather

There is a need to improve the equipment, programmes and forecasting tools used to provide weather information. These include, for example, the installation of Automatic Weather Systems (AWSs), sourcing of satellite products, improving and upgrading Numerical Weather Prediction (NWP) models and installation of a network of weather radars.

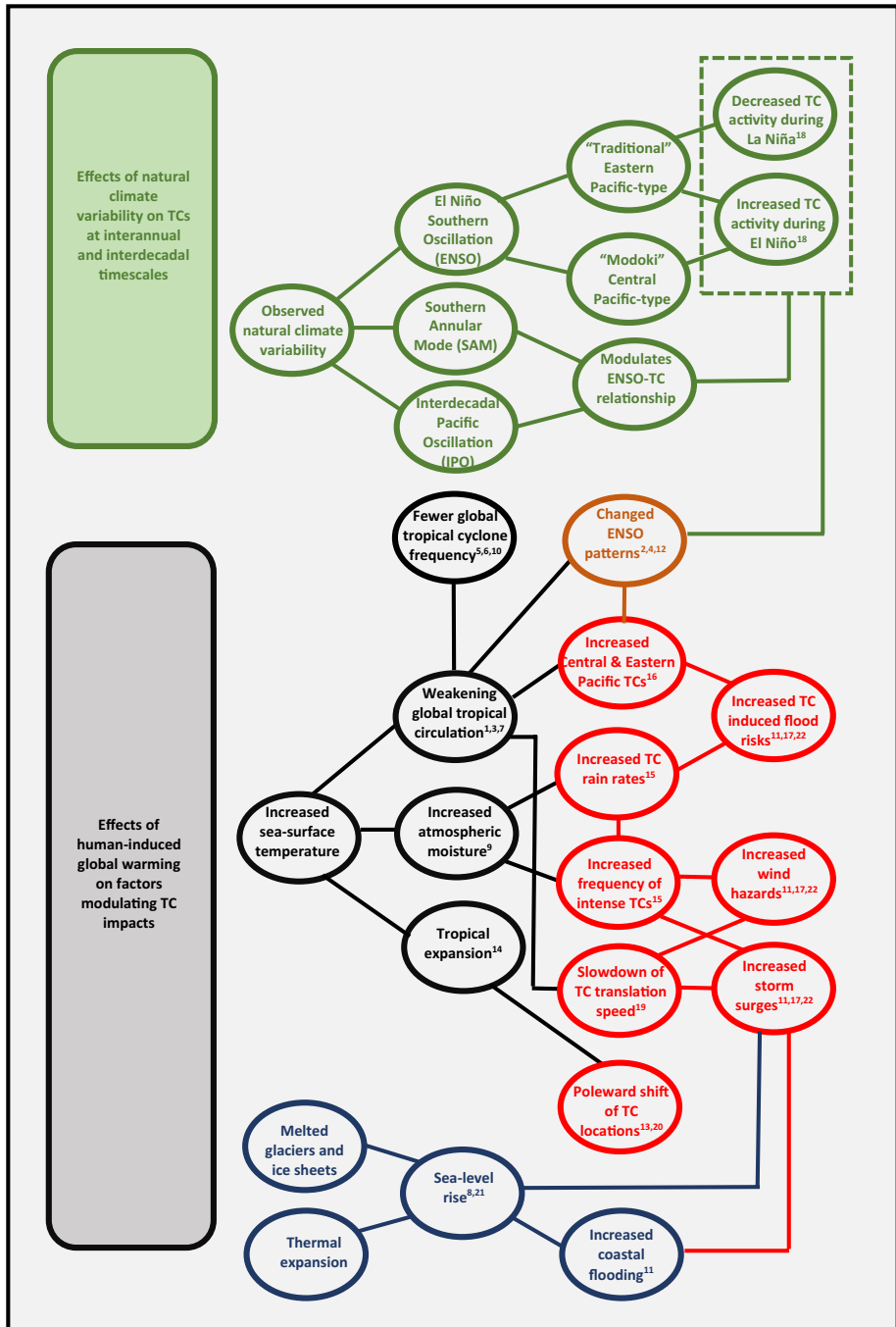
- Home retrofitting and building back better

While not associated with NHMS, it is important to mention here that home retrofitting could also aid mitigation, prevention and preparedness. Approximately 30,369 houses, 495 schools and 88 health clinics and medical facilities were damaged or destroyed during the passage of TC *Winston*. Assessing the photos (e.g. Fuata (2016)) show that some structures have suffered major damages mostly to the roofing and openings (e.g. windows). To mitigate such effects of strong winds, owners could have their buildings assessed by professionals and accordingly retrofit these structures with necessary reinforcing materials (such as hurricane straps and roofing screws). While there is no guarantee that these measures will provide an absolute protection during the passage of a TC, they nonetheless substantially decrease the likelihood of damage during these events compared to when not implementing them.

3.6 TC decision-support framework in the context of a changing climate

Understanding the likely changes in TC characteristics at regional and local scales due to global warming is challenging. This is at least in part due to the lack of long-term TC records in the Pacific for detection and attribution of climate change signals (Knutson et al. 2019) and partially because of the large deficiencies and biases in climate model simulations of regional and local-scale TCs (Wang et al. 2014). Reliable observations of TCs became available only from around the 1970s when satellite monitoring became operational, but these few decades of data are not sufficient to adequately resolve climate change signals particularly in the presence of large climate variability across and between decades (Klotzbach and Landsea 2015; Moon et al. 2019).

Moreover, global climate models are not typically run at scales needed to resolve changes in TC characteristics (particularly intensity) at island-scale, substantially limiting our ability to understand the effects of climate change on TCs over small island countries



in the SWP region. Nevertheless, from past literature (Vecchi et al. 2006; Power and Kociuba 2011; Sugi and Yoshimura 2012; Tokinaga et al. 2012; Tory et al. 2013; Woodruff et al. 2013; Kossin et al. 2014; Lucas et al. 2014; Walsh et al. 2016; Chand et al. 2017;

Chand 2018; Kossin 2018; Sharmila and Walsh 2018; Lee et al. 2021), trends in observation records, climate model simulations and theoretical understanding, we have a good understanding of how various climatic conditions may interact to affect TCs and associated impacts in the SWP region as depicted in Fig. 5. It is important to note here that this schematic does not make any attempt to quantify the changes, but instead demonstrates how different climatic factors may interact to affect TC characteristics and associated impacts in the SWP region.

The level of risk associated with a TC event is already very large across the SWP region as shown earlier, and TC-induced risks are likely to exacerbate further as a consequence of global warming, particularly during future-climate El Niño periods. The increasing threats from storm surge and coastal flooding due to sea-level rise should be of concern for atolls and islands, particularly those located within the TC-impact zones (e.g. Cook Islands, Fiji, Samoa, Solomon Islands, Tonga and Vanuatu). Such threats can also have direct consequences on long-term food and water security for the atoll and island communities, for example through intrusion of saltwater into freshwater storages and cultivable land, creating irrecoverable damages to the livelihood, and in some cases through permanent loss of islets (Hisabayashi et al. 2018).

Climate change adaptation planning for managing future TC-induced impacts can be very complicated for highly vulnerable atoll and island countries in the SWP region. However, some recent events, such as those associated with TC *Pam* and TC *Winston*, can present a window of opportunity to trigger transformational changes in the communities' approach to TC-induced risks and impacts. These transformational changes can range from developing quintessential strategies for mitigating immediate impacts of TCs—such as emergency shelters and effective evacuation procedures—to long-term technological and engineering solutions—such as seawalls, levees, desalination plants and storm water harvesting—to mitigate effects of rising sea-level and storm surges, and their potential impacts on food and water security.

3.7 Recommendations

Pacific Island Countries and Territories (PICTs) are taking collective action towards developing a regional TC preparedness and response framework via the Pacific Meteorological Council (PMC). The PMC is a specialised body of the Secretariat of the Pacific Regional Environment Programme (SPREP) comprised of the directors or heads of PICT meteorological services that was established in 2011 to facilitate and coordinate the scientific and technical programme and activities of the Pacific island region's meteorological services. At the most recent biennial PMC meeting held in Samoa in 2019, the Pacific Islands Climate Services (PICS) Panel⁶ of the PMC identified the need to work towards an agreement between PICTs' National Meteorological and Hydrological Services (NMHS) and regional providers (i.e. Fiji Meteorological Service, National Institute of Water and Atmospheric

⁶ Six PMC Expert Panels provide technical advice to the Council on matters concerning the development of meteorological services in the region under each thematic area of the Pacific Islands Meteorological Strategy 2017–2026; Pacific Island Climate Services (PICS) Panel, Pacific Island Marine and Oceans Services (PIMOS) Panel, Pacific Island Aviation Weather Services (PIAWS) Panel, Pacific Island Communications and Infrastructure (PICI) Panel, Pacific Island Education, Training and Research (PIETR) Panel, Pacific Hydrological Services (PHS) Panel.

Research (NIWA) of New Zealand and the Australian Bureau of Meteorology) on a more coordinated release process and timeline for SWP TC outlooks.

The PMC identified two priority opportunities for improving seasonal TC preparedness communication; (i) regional providers were prone to disseminate regional and country TC outlooks before NMHS have had an opportunity to prepare their own TC outlook statements and media releases, and (ii) each provider uses a different methodology and different boundaries leading to different outlooks and thus some confusion amongst users. To address the first issue, PMC has worked with regional providers to make embargoed draft TC outlooks available to NMHS a week prior to release, enabling NMHS to tailor local language media releases that facilitate local understanding and uptake of regional TC outlook products. On the second issue, PICS has released good practice guidelines (PICS Panel 2020) for producers and users of SWP TC outlooks that include recommendations to prioritise user needs over scientific interest and to engage with stakeholders to determine their capacity to interpret scientific and multi-model information.

To further enhance communication of seasonal TC preparedness, the WMO Regional Association Five (RA-V) Pacific Regional Climate Centre (RCC) Network⁷ has published an online ENSO tracker (RCC 2020) product that gathers and summarises the status of ENSO according to different global institutions and combined with other educational and awareness products, like the TC outlooks, can help PICTs' stakeholders better understand their seasonal TC risk. The Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) together with SPREP and other partners have also published a Pacific-themed, animated video called the 'Adventures of the Climate Crab' (CSIRO 2013) in multiple Pacific languages that explain to a general audience ENSO and its effects on PICTs' Seasonal TC risk and how to prepare. It is important to ensure that such products and services are culturally appropriate, understandable by the intended audience, and tailored to stakeholders' needs.

While NMHS are responsible for transmitting seasonal and event-scale TC information, many Pacific communities have difficulty understanding the information provided, have delayed access to weather and climate information, have access but mistrust the accuracy of the information by NMHS, or have no access to any information provided by NMHS due to remoteness or isolation of communities (Lui et al. 2017; Plotz et al. 2017; Chambers et al. 2019). Thus, many remote Pacific communities rely on weather and climate forecasts based on traditional knowledge (TK) alone or in combination with contemporary (NMHS) forecasts (Magee et al. 2016; Chambers et al. 2019). When category 5 TC Zoe (2002), the second most intense TC ever recorded in the Southern Hemisphere at that time, devastated the Solomon Islands outliers of Tikopia and Anuta in 2002, islanders without access to NMHS forecasts or warnings relied on TK to survive the disaster without the loss of a single life (France-Presse 2003; SPREP 2019). Tikopian Elders were able to use TK of unusual movements of ocean currents and bird behaviour to forecast the coming TC and evacuate the community to caves where they sheltered safely until TC Zoe passed (SPREP 2019).

When designing a TC decision-support framework for PICTs, the incorporation of traditional forecast methods into contemporary forecast systems can lead to forecasts that are

⁷ The WMO RA-V Pacific Regional Climate Centre (RCC) Network is a virtual Centre of Excellence that assists National Meteorological and Hydrological Services (NMHS) in the Pacific Islands region to deliver better climate services and products and to strengthen their capacity to meet national climate information and service delivery needs.

locally relevant and better trusted by the users, which in turn could significantly improve the communication and application of climate and weather information, especially to remote communities (Chand et al. 2014; Plotz et al. 2017). Thus, Plotz et al. (2017) recommend that such a framework comprises of four main decision points: (1) consideration of the level of involvement of traditional-knowledge experts or the community that is required; (2) existing levels of traditional knowledge of climate forecasting and its level of cultural sensitivity; (3) the availability of long-term data—both traditional-knowledge and contemporary-forecast components; and (4) the level of resourcing available.

There is no one-size-fits-all approach when it comes to developing climate change adaptation and mitigation strategies, particularly for highly vulnerable communities where TC-induced impacts are of a major concern. Drawing on experiences from past TC events as analogies to what may happen in the warming climate is imperative. Such activity should emphasise a ‘bottom-up’ approach (Pielke Sr et al. 2012) that requires local community and stakeholder-led discussion to first determine and evaluate the level of TC-induced threats to critical local factors like food and water security, and then develop relevant and relatable adaptation and mitigation strategies for each factor. Moreover, strategy development for adaptation planning processes needs to be an iterative process to take into account updated science on climate extremes. Adaptation decisions are not static but need to be themselves ‘adaptive’ to new information and knowledge (Morioka et al. 2020). Moving forward, it is critical that relevant national agencies (such as NHMS, NDMO and Department of Climate Change) understand the differences in the likelihood of TC occurrences between different climatic conditions (e.g. El Niño and La Niña periods) and clearly communicate this to sector stakeholders and the wider community through their information products and awareness-raising. Such approaches are believed to be a more inclusive way of assessing impacts of TCs and adopting more effective adaptation methodologies to deal with the complexity of potential extreme events affecting the SWP region.

4 Summary

Normalised economic losses (based on wealth and population) and fatalities during the passage of TCs in close proximity to the Fiji, Samoa, Tonga and Vanuatu (FSTV) region for the period 1970–2018 have been investigated in this study. An increasing trend in normalised economic loss due to TCs over the study period is not evident for most nations, except for Fiji where TC *Winston* in 2016 caused the most damage (USD 0.9 Billion) to the nation. Moreover, TC *Val* (1991), *Gita* (2018) and *Uma* (1987) caused the most extensive economic losses over Samoa (USD 1.782 Billion), Tonga (USD 0.146 Billion) and Vanuatu (USD 0.922 Billion) respectively. Hence, TC *Val* (1991) could be considered the costliest TC over the FSTV region. In terms of fatalities, the largest number of severe TC-associated deaths has occurred over Fiji and Vanuatu at 52 and 50 during TC *Meli* (1979) and TC *Uma* (1987) respectively. For Samoa and Tonga, the highest numbers of fatalities of 14 and 6 were due to TC *Evan* (2018) and TC *Isaac* (1982) respectively. Trends in fatalities are an important indicator of the overall improvements in the DRR and DRM over time, and this was examined here using the ratio of fatality to normalised economic loss. A decreasing trend in this index is generally evident, which signifies that there have been improvements in DRR and DRM over time in the FSTV region.

TC *Winston* has been used as a case study to illustrate the disaster preparedness and response during a TC event over the FSTV region and future recommendations have been

suggested to reduce impacts during the passage of TCs. These recommendations include (i) increasing public awareness and individual preparedness, (ii) upgrading the current tools used to observe and forecast weather and (iii) home retrofitting. The discrepancy in fatalities between ethnic groups during TC *Winston* also requires further investigation and appropriate measures for future disaster TC responses.

Finally, we discussed the collective action taken by Pacific Island Countries and Territories (PICTs) towards developing a regional TC preparedness and response framework via the Pacific Meteorological Council (PMC). In particular, when designing a TC decision-support framework for PICTs, the incorporation of traditional forecast methods into contemporary forecast systems can lead to forecasts that are locally relevant and better trusted by the users, which in turn could significantly improve the communication and application of climate and weather information, especially to remote communities. Such a framework should comprise four main decision points: (1) consideration of the level of involvement of traditional-knowledge experts or the community that is required, (2) existing levels of traditional knowledge of climate forecasting and its level of cultural sensitivity, (3) the availability of long-term data—both traditional-knowledge and contemporary-forecast components—and (4) the level of resourcing available.

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Data availability The datasets generated during and/or analysed during the current study could be obtained from the respective Government's TC Disaster Assessment and NHMS reports. Several of these reports are archived at the United Nations Office for the Coordination of Humanitarian Affairs' (UN-OCHA) 'ReliefWeb' portal (<https://reliefweb.int/>).

Declarations

Competing interests The authors declare no competing interests.

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